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THE DIRECT DRIVING OF SYNCHRONOUS GENERATORS BY LARGE SCALE WIND ELECTRICAL POWER GENERATING PLANTS IN PARALLEL OPERATION WITH A SYNCHRONIZING NETWORK

(Part I)

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THE DIRECT DRIVING OF SYNCHRONOUS GENERATORS
BY LARGE SCALE WIND ELECTRICAL POWER GENERATING
PLANTS IN PARALLEL OPERATION WITH A SYNCHRONIZING NETWORK*

Max Kloss **

INTRODUCTION

When wind energy is exploited by wind generating stations which then converts the energy into electrical power, there is the difficulty associated with the rotation rate variation of the propeller wheel and the rotation rate behavior of the electrical generator. It is assumed that the rotation rate of the propeller wheel is proportional to the wind velocity and that the torque increases as the square of the wind velocity. Generators supplying a network usually operate at a constant rotation rate so as to provide a constant voltage. Apparently these two operational characteristics contradict each other. Conditions are not so bad for direct voltage, because in this case it is possible to equalize fluctuations in the rotation rate within certain limits without any difficulty. This is done by changing the excitation in a corresponding way. Within these limits, it is then possible to obtain practically the same voltage. /362***

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** VDE, Berlin

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In the case of three phase voltage, on the other hand, not only must the voltage be held constant but also the frequency. This must be done accurately and not approximately. This leads to the conclusion that because of the basic differences in the operational characteristics, it is not possible to directly drive synchronous generators by wind generating systems.

Various solutions have been proposed to overcome this contradiction: first of all, asynchronous generators have been used instead of synchronous generators in order to eliminate the requirement for a constant rotation rate. For example, such installations have been built in Russia [1]. In a second solution, a transformer installation with a grid controlled alternating rectifier was switched in between the three phase generator operating at a variable rotation rate and the net. This converter unit transforms the fluctuating voltage brought about by the change in rotation rate and the fluctuating frequency to a constant value required by the net. For example, this solution was selected by Kleinhenz in collaboration with the machineworks Augsburg-Nürnberg (MAN) and the firm Brown, Boveri and Cie (BBC), Mannheim, for the design of a large scale wind generating plant. Certainly this is a technical solution. However, the transformer installation contains numerous transformers, rectifiers, switching and control units which will increase the costs and reduce the efficiency. Also it is much more complicated and requires more maintenance.

It was Dr. Kade, Director of the firm BBC, who proposed a second design for the same wind generating station. He recognized that the discrepancy between the operational characteristics of the wind generating station and the operational characteristics of the synchronous generator was nothing more than personal bias.

At the request of the "Wind Energy Reichs group",* we will now make a more detailed analysis of the problem in the following. First of all we will prove that it is actually possible to operate a synchronous generator with a wind propeller wheel at a constant rotation rate. Then we will investigate the adjustment process to a new equilibrium state which occurs when the wind velocity changes. We will also discuss methods of controlling the power output, in particular methods of maintaining the nominal power level constant over a wide range of wind velocity.

Of course we assume that the generator is to operate in parallel with an available network supplied by synchronous machines, which requires that the voltage and frequency remain constant.

I. Eigen Oscillations of a Synchronous Generator Operating in Parallel with a Fixed Network

1. Differential Equation for the Oscillation Process and Determination of the Eigenvalues

The differential equation of a damped oscillation of a mass M around an equilibrium position (x = 0) is

$$-M\frac{d^2x}{dt^2} - D_k\frac{dx}{dt} - Sx = 0, \qquad (1)$$

where

x   deflection from the equilibrium position, in our case measured around the circumference of the pole wheel

$\frac{dx}{dt}$ oscillation velocity, i.e., the slip of the pole wheel with respect to its synchronous velocity, where oversynchronous conditions are referred to as positive slip so as to be able to apply the sign convention in a consistent way (in contrast to what is done when asynchronous machines are analyzed).

* The Reichs group "Wind Energy" (RAW) is an honorary group of advisery specialists.

The first term $-M\frac{d^2x}{dt^2}$ is the inertia force of the mass M which occurs for positive acceleration $\frac{d^2x}{dt^2}$ and which opposes the acceleration. The second term $-D_k\frac{dx}{dt}$ is the damping force which is opposed to the slip and proportional to it (starting at the damping unit located at the pole shoes), that is

D_k damping force for the oscillation velocity

$$\frac{dx}{dt} = 1.$$

The third term $-Sx$ is the so called "control force" or the "synchronizing force" which attempts to return the mass M which has been deflected from the equilibrium position by the amount x back to the equilibrium position, that is,

S control force for the deflection $x = 1$.

In order to apply this basic equation from mechanics to our problem it is necessary to express the quantities D_k and S by generator variables.

If we introduce the "damping moment" D_m and if the oscillation rate $\frac{dx}{dt} = R\,\omega_s$ is expressed by the synchronous angular velocity $\omega = \frac{\pi n}{30}$ and the "slip" $\sigma = \frac{\omega_s}{\omega}$ (R radius of the pole wheel), then we have

$$D_k = \frac{30}{\pi n R^2}\left(\frac{D_m}{\sigma}\right). \tag{2}$$ /363

The expression D_m/σ can be represented by introducing the slip σ_n, at which the damping moment D_m becomes equal to the nominal torque M_{d_n} of the generator, that is

$$\frac{D_m}{\sigma} = \frac{M_{d_n}}{\sigma_n} \tag{3}$$

(for any machine this is a fixed variable).

In this way we obtain

$$D_k = \frac{30}{\pi n R^2}\left(\frac{M_{d_n}}{\sigma_n}\right). \qquad (2a)$$

In addition, the control force S for the deflection x = 1 can be expressed in terms of the generator variables

- p number of pole pairs
- k_v short circuit ratio referred to full load excitation
- M_{d_n} nominal torque
- ϑ lead angle of the pole wheel, referred to the two pole machine for nominal load

We then obtain the following for S

$$S = \frac{p\, k_v\, M_{d_n}}{R^2}\,\frac{\cos\vartheta}{\cos\varphi}\,. \qquad (4)$$

The lead angle ϑ and the short circuit ratio k_r can be taken from the well known circulation vector diagram shown in Figure 1. This diagram only shows the basic relationships and does not indicate the well known Blondel decomposition of the armature circulation into the transverse and longitudinal field. It also does not consider the ohmic voltage drop nor the increase in the pole scatter.

The following definitions apply in the figure. In the figure we have:

- ϕ the useful flux through the armature winding
- E vector of machine voltage (90° lag with respect to Φ)
- J current vector with a phase lag φ with respect to the voltage

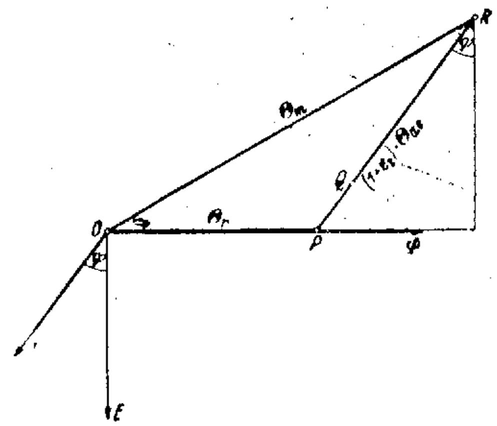

Figure 1. Simplified circulation of the synchronous generator
ϑ advance angle of the pole wheel.

OP Θ_r the resulting circulation required for exciting the flux Φ along the principle path, which consists of the two components OR and RP. We have

OR Θ_m circulation through the magnetic excitation winding of the pole wheel,

RP $(1+\varepsilon_s)\Theta_{ae}$, armature flux (RQ = Θ_{ae}) recalculated for uniform excitation circulation parallel to the current vector, increased by the excitation circulation required for driving the armature flux through the air gap $QP = \varepsilon_s \Theta_{ae}$

ϑ lead angle of the pole wheel (for the two pole machine) with respect to the zero load position which has the direction Φ.

From the diagram we have obtained the following expression for the short circuit ratio referred to full load excitation conditions

$$k_\varphi = \frac{OR}{RP} = \frac{\Theta_m}{(1+\varepsilon_s)\,\Theta_{ae}}\,.$$

2. The Eigen Oscillation Period

According to the laws of mechanics, the Eigen oscillation period without any damping can be obtained from the mass and the restoring force, as follows

$$T_e = 2\pi\sqrt{\frac{M}{S}} \text{ or } = \frac{2\pi}{\sqrt{\frac{S}{M}}}, \tag{5}$$

that is with Equation (4)

$$T_e = 2\pi\sqrt{\frac{M R^2}{p\,k_v\,M_{d_n}}\,\frac{\cos\varphi}{\cos\vartheta}} = 2\pi\sqrt{\frac{I}{p\,k_v\,M_{d_n}}\,\frac{\cos\varphi}{\cos\vartheta}}, \tag{6}$$

where $I = MR^2$ is the polar moment of inertia of the flywheel masses referred to the pole wheel diameter. We obtain the moment of inertia as follows from the "flywheel moment" GD^2

$$I = \frac{GD^2}{4g}\,. \tag{7}$$

If there is damping, the Eigen oscillation period (which is also constant) becomes

$$T_{ed} = \frac{2\pi}{\sqrt{\frac{S}{M} - \frac{D_k^2}{4M^2}}} = \frac{2\pi}{\sqrt{\frac{S}{M}}\sqrt{1-\frac{D_k^2}{4MS}}} = \frac{T_e}{\sqrt{1-\delta^2}}\,, \tag{8}$$

where the numerical factor is $\delta = \frac{D_k}{2\sqrt{MS}}$ (9)

By substitution of the values from Equations (2 a) and (4) we obtain

$$\delta = \frac{30}{2\pi n a_n}\sqrt{\frac{M_{d_n}\cos\varphi}{p k_v I \cos\vartheta}}. \tag{10}$$

3. The Equation for the Damped Oscillation

We will assume that the pole wheel has been deflected backwards from the equilibrium position corresponding to the nominal load. This is done by a sudden pulse. It is assumed that synchronous conditions prevail for this position. This means that $-A_o$ is the amplitude of the backwards deflection at the time $t = 0$ which means that the solution of the differential Equation (1) is given by

$$x = -A_0 e^{-y\frac{t}{T_{ed}}}\cos\omega_{ed} t,$$

where the angular velocity ω_{ed} can be expressed in terms of the Eigen oscillation period T_{ed} as follows: $\omega_{ed} = \frac{2\pi}{T_{ed}}$; therefore we have

$$x = -A_0 e^{-y\frac{t}{T_{ed}}}\cos 2\pi\frac{t}{T_{ed}}. \tag{11}$$

As is known, this equation corresponds to a damped harmonic oscillation, the amplitude of which decreases according to the well known e function, (for example this occurs in the cooling of a heated body).

We find the following for the exponent factor y (in the relationship e^{-y}, it is the ratio of two subsequent oscillation amplitudes in the same direction).

$$y = \frac{D_k T_{ed}}{2M}. \tag{12}$$

By dividing (12) by (9) and substitution of (5), we find

$$\frac{\nu}{\delta} = T_{ed}\sqrt{\frac{S}{M}} = 2\pi\frac{T_{ed}}{T_e},$$

that is

$$\nu = 2\pi\delta\left(\frac{T_{ed}}{T_e}\right). \tag{13}$$

This means that Equation (11) becomes

$$x = -A_0 e^{-2\pi\delta\frac{t}{T_e}} \cos 2\pi\frac{t}{T_{ed}}. \tag{14}$$

If the "time constant" T is introduced in order to represent the /364
decay, according to the logarithmic curve, we find

$$x = -A_0 e^{-\frac{t}{T}} \cos 2\pi\frac{t}{T_{ed}}, \tag{15}$$

and from (14) and (15) we find the time constant for decay as follows

$$T = \frac{T_e}{2\pi\delta}. \tag{16}$$

4. The Largest Forward Deflection and the Largest Slip

In order to evaluate the highest transient overload, it is necessary to determine the largest forward deflection (angle). It occurs during the first forward oscillation, that is at the time $t = \frac{T_{ed}}{2}$ where $\cos 2\pi\frac{t}{T_{ed}} = \cos\pi = -1$. This means that it amounts to

$$A_k = A_0 e^{-\pi\delta\frac{T_{ed}}{T_e}}. \tag{17}$$

In addition, in order to evaluate the deviation of the machine from synchronous conditions during the oscillations, it is necessary to know the largest possible slip. This occurs at the time of first transition through the equilibrium position, that is for x = 0 at t = $\frac{T_{ed}}{4}$, that is $\cos 2\pi \frac{t}{T_{ed}} = 0$. This means that the maximum oscillation velocity becomes

$$v_{s_m} = \left(\frac{dx}{dt}\right)_{x=0} = \frac{2\pi}{T_{ed}} A_0 e^{-\frac{t}{T}} \sin 2\pi \frac{t}{T_{ed}} = \\ = \frac{2\pi}{T_{ed}} A_0 e^{-\frac{T_{ed}}{4T}}.$$

We now introduce the following $a_{s_m} = \frac{\vartheta_{s_m}}{p}$ which is the largest angular deflection during the oscillation of the pole wheel in arc units. This corresponds to the linear deflection

$$A_0 = a_{s_m} R = \frac{\vartheta_{s_m}}{p} R, \tag{18}$$

where (illegible) is the largest angular deflection referred to the two pole machine at the beginning of the oscillation (t = 0). This means that by substituting the value t = $T_{ed}/4$ we find

$$v_{s_m} = \frac{2\pi}{T_{ed}} \frac{\vartheta_{s_m}}{p} R e^{-\frac{T_{ed}}{4T}}.$$

We divide this by the synchronous velocity $v = \frac{2\pi R n}{60}$ and find the desired maximum slip

$$\sigma_m = \frac{60}{p n} \frac{\vartheta_{s_m}}{T_{ed}} e^{-\frac{T_{ed}}{4T}},$$

or when $\frac{pn}{60} = f$ (frequency):

$$\sigma_m = \frac{\vartheta_{s_m}}{f T_{ed}} e^{-\frac{T_{ed}}{4T}}. \tag{19}$$

For small angular deflections of the oscillation, we can assume that this is proportional to the torque change, that is,

$$\frac{\vartheta_{\kappa_m}}{\vartheta} = \frac{M_{d_1} - M_{d_n}}{M_{d_n}} = \frac{M_{d_1}}{M_{d_n}} - 1, \tag{20}$$

where $M_{d_1} - M_{d_n}$ is the excess torque for the deflection $-A_o$.

5. Numerical Example for Determining the Order of Magnitude of the Characteristic Variables

According to the predesign II of the firm BBC for the project Kleinhenz-MAN, for a generator with the characteristics

$$12\,500 \text{ kVA} \quad 10\,000 \text{ kW} \quad \cos\varphi = 0{,}80 \quad 5250 \text{ V} \quad 50 \text{ Hz}$$

at n = 12 rpm 2 p = 500 poles

the moment of inertia of the pole wheel is

$$GD^2 = 60\,000 \text{ tm}^2;\; I = 1{,}53 \cdot 10^6 \text{ kgms}^2$$

and of the propeller wheel it is

$$= 420\,000 \text{ tm}^2;\; I = 10{,}7 \cdot 10^6 \text{ kgms}^2$$

that is the total moment of inertia is

$$480\,000 \text{ tm}^2;\; I = 12{,}23 \cdot 10^6 \text{ kgms}^2.$$

For "electrical efficiency" of $\eta_e = 0{,}90$, the mechanical nominal power level is $N = \frac{10 \cdot 10^6}{0{,}90} = 11{,}1 \cdot 10^6 \text{ W}$ and therefore the nominal torque is

$$M_{d_n} = 0{,}973 \frac{N}{n} = 0{,}90 \cdot 10^6 \text{ kgm}.$$

The short circuit ratio (corresponding to modern practice) referred to the nominal low excitation and for the conditions shown in Figure 1 is assumed to be $k_\nu = 1.6$. The lead angle ϑ is 30° and $\cos \vartheta = 0.866$.

Using these values, and with Equation (6) we obtain the following Eigen oscillation period without damping

for the pole wheel alone $T_e = 0{,}394$ s,
for the pole wheel and the propeller wheel $T_e = 1{,}11$ s.

We can therefore see the large influence of the propeller wheel mass. In order to determine the Eigen oscillation period with damping, it is first necessary to calculate the value of δ. According to the design data, the damping characteristics are such that the damping torque equals the nominal torque Md_n for a slip of $\sigma_n = 5\,\% = 0{,}05$. Therefore according to Equation (10) we find

$$\delta = 0.104$$

(For the pole wheel alone we would find $\delta = 0.294$).

Therefore according to Equation (8) we find the following Eigen oscillation period with damping

for the pole wheel alone	$T_{ed} = 0.413$ s,
for pole wheel and propeller wheel	$T_{ed} = 1.115$ s.

According to this, the difference between T_{ed} and T, for the pole wheel alone amounts to only 4.5%. For the pole wheel and the propeller wheels together, this amounts to less than 1/2%. This means that it can be ignored (this means that Equation (13) for the factor y simplifies to $y = 2\pi\delta$) .

According to Equation (16) the time constant $T = \frac{T_e}{2\pi\delta}$, for the decay of the oscillation is as follows:

for the pole wheel alone $T = \frac{0{,}394}{2\pi\, 0{,}294} = 0{,}213\ s$,

for the pole wheel + propeller wheel $T = \frac{1{,}111}{2\pi\, 0{,}104} = 1{,}70\ s$.

This means that the time constant for the pole wheel alone is more than the eigen oscillation period. For the total mass with the propeller wheel it is larger than T_e, that is + $1.53 \cdot T_e$. The large mass therefore slows down the decay of the oscillation considerably.

After about four time constants, the e function has practically decays entirely. This means that the pole wheel together with the propeller wheel, after having been subjected to a sudden pulse which would throw it out of the equilibrium position, would have reached the final oscillation conditions corresponding to equilibrium after about 7 seconds.

If the largest (backwards) deflection produced by the pulse $-A_0$, the largest forward deflection according to Equation (17), which is decisive for the transitory load, becomes the following if we consider the fact that $T_{ed} \approx T_e$,

$$A_h = A_0\, e^{-\pi\delta} = A_0\, e^{-0{,}327} = 0{,}72\, A_0 .$$

II. Influence of the Propeller Wheel Characteristic of the Development of the Transient Oscillation Process

1. Characteristic of the Propeller Wheel

The characteristic shown (Figure 2) gives the variation of the torque delivered by the propeller wheel as a function of its rotation rate, assuming constant angular rate v. It is appropriate to use the ratio of the rotation rate n/n_n with respect to the nominal rotation rate of the generator, and not the rotation rate itself as the abscissa value. We use the ratio /36
of the torque to the nominal torque M_{d_n} for the nominal output level of the generator M_d/M_{d_n}, for the ordinate. The curve is then not restricted to any special case, but can be applied for the general case. When the wheel is unloaded, the rotation rate increases. For complete unloading, it would take on the value corresponding to Point A, the "racing rotation rate". In practical applications, it is assumed that this point corresponds to about 1.85 times the nominal rotation rate. Of course this is not a fixed value. Instead it depends on which point of the characteristic the "nominal load" is located (Point B). For our discussion and based on characteristics published in the open literature, we can assume that the variation corresponds to a straight line with a sufficient degree of accuracy. Even if the true characteristic deviates from the straight line for real loadings, this does not make any difference for our case because in this range the generator is not loaded. For our investigations, only the inclination of the characteristic at the load point is important as we will show below.

When the rotation rate decreases, the propeller wheel torque increases further. It follows from the flow conditions that at a certain rotation rate a maximum value occurs (Point K). After this point, the torque decreases again with decreasing rotation rate. The propeller wheel therefore behaves like an asynchronous

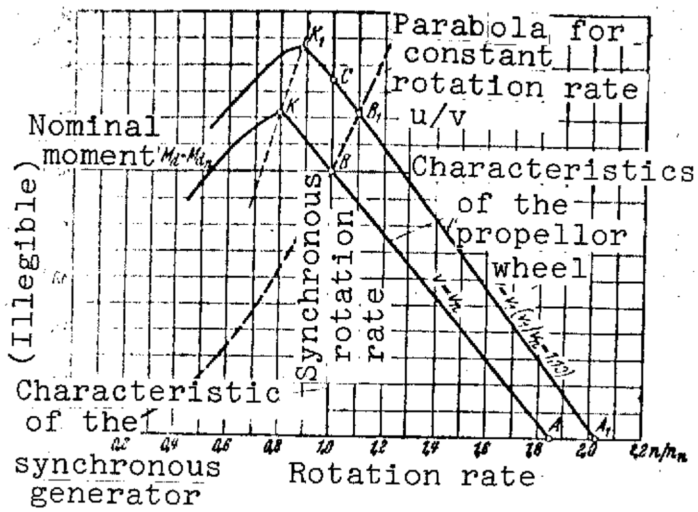

Figure 2. Operational characteristics. Determination of the stable load states

three phase motor, which also first has a torque which is approximately proportional to the slip. At a certain value of the slip, a maximum value (tipping moment) is reached, after which it decreases again. If the propeller wheel were to drive a machine, the torque of which is independent of the rotation rate, then at Point K it would "break away" and would stand still.

Before we investigate the behavior of the propeller wheel when it is driving a synchronous generator, we must first answer the question of how the characteristic of the propeller wheel changes when the angular velocity is changed.

In aerodynamics an additional variable, the so-called "pitch" = u/v, is introduced where u is the circumferential velocity of the propeller wheel and v is the wind velocity. Since for each characteristic v = const., but u changes with n, the pitch ratio has a different value for each point of the characteristic. As a rule, the normal working point along the characteristic is selected (the so-called "design power"). In this way, the evaluation factor for wind exploitation becomes as large as possible. This point is to the right of the breakaway Point K, let us assume that it is at Point B. A certain value of the pitch ratio u/v corresponds to it. When the wind velocity v is changed, for example from v_n to $v_1 = 1.10\ v_n$, then for the same pitch, that is for the same flow conditions, u and therefore also the rotation rate n would change proportionally, that is

$n_1 = 1.10\ n_n$. The torque, on the other hand, increases as the square of velocity, that is $\frac{M_{d_1}}{M_{d_n}} = \left(\frac{v_1}{v_n}\right)^2 = \left(\frac{n_1}{n_n}\right)^2$. With these assumptions, the working Point B is displaced to the Point B_1, according to the parabola law, which is then a point of the new characteristic for $v_1 = 1.10 \cdot v_n$. Also, the breakaway Point K moves along a parabola to K_1. The intersection Point A for $M_d = 0$ is displaced linearly along the abscissa axis at a ratio of 1.10, that is from 1.85 to 2.035 to the Point A_1. In this way, one obtains the new characteristic which is displaced upwards and to the right with respect to the old one.

The parabola law mentioned (which is also applied to ventilators and rotary pumps) is well known and has been accepted in a sense that a change in the wind velocity does not always always bring about a corresponding change in the rotation rate. It was this erroneous idea, as mentioned in the introduction, which led persons to believe that it would be impossible for a wind propeller to drive a synchronous generator, because it could not satisfy the condition for maintaining constant frequency, that is a constant rotation rate for all loads. This idea contradicts the parabola law mentioned above. However, this is a false conclusion. This false conclusion consists of the fact that the parabola law only applies under certain conditions: this is the condition for unchanged flow conditions, that is constant pitch ratio u/v. This is not an external condition placed on the propeller wheel. Otherwise, the "characteristic" of the propeller wheel could not exist at all. As mentioned above, each point corresponds to a different pitch ratio.

When a synchronous generator is driven, we must always have equilibrium between the torques of the propeller wheel and the torque of the generator.

2. The Equilibrium State when Driving a Synchronous Generator

The load Point B_1 derived from the Point B which corresponds to the new characteristic is not a stable load point. This is because an increase rotation rate corresponds to it. The synchronous generator has a constant rotation rate $n = n_n$, i.e., its characteristic is a straight line parallel to the ordinate axis at the point $n/n_n = 1$, (see curve in Figure 2). A stable equilibrium only occurs at the intersection point of the two characteristics, that is for the wind velocity $v = v_n$ at the Point B, for $v_1 = 1.10\ v_n$ at the Point C. The diagram shows that for the assumed conditions, when there is a 10% increase in the wind velocity, there is an increase in the load moment by a factor of 1.34, which is considerably greater than would correspond to 1.21 according to the square law. The increase is somewhat larger than the third power of the wind velocity. However, this is not a value which is fixed. Instead it depends on the inclination of the characteristic, or on the points on the characteristics selected for the nominal power output. For example, if a synchronous rotation rate were to be selected in such a way that the nominal load point would coincide with the breakaway Point K of the propeller wheel, then the load point of K (with a relative value of 1.21) would be displaced to the point vertically above it along the second characteristic (having the relative value of 1.43). Then the load of the generator would be increased to a value $\frac{1{,}43}{1{,}21} = 1{,}18$ larger than before. This would be an increase which would be less than would correspond to the square of the wind velocity ratio.

These results are extremely important because they form the basis for discussing the question of by how much the generator is overloaded when the wind velocity is increased.

It also answers the question of what measures must be taken to prevent acceptable overloads, which will be discussed in more detail in Section III.

There is an increase in the lead angle of the pole wheel which corresponds to the new equilibrium point C and the new generator load moment. How does the device adjust to the new load state?

3. The Transient Oscillation Process

For simplicity, we will first discuss the most unfavorable case (which never occurs in reality), in which the angular of velocity v_n (corresponding to Point B) suddenly changes to v_1 (in the representation we assume $v_1 = 1.10\ v_n$). In this case, the propeller wheel delivers a (illegible) torque $M_{d_1} - M_{d_n}$ corresponding to the distance BC above the previous load moment M_{d_n} of the generator.

It is appropriate to consider the transient oscillation process not beginning with the equilibrium position which had prevailed, but to start with a new equilibrium position, around which the transient oscillation process varies. Accordingly, the pole wheel at the beginning of the process has a negative oscillation amplitude (lag). Therefore we are not discussing the case described above in which the pole wheel was given a position by a pulse (which would have a braking effect here). Since the wheel is running at the synchronous velocity, the amplitude represents the first oscillation in the backwards direction. This means that $x = -A_o$ for $t = 0$. /366

Because of the influence of the excess moment of the propeller wheel $M_{d_1} - M_{d_n}$ = distance BC in Figure 2, the pole wheel is accelerated. This acceleration is opposed by the force of inertia $-M\frac{d^2x}{dt^2}$ of the total mass, like before [first term in Figure (1)].

The excess torque mentioned above is the "control force" (illegible) which has a positive effect because of the negative deflection x, as observed from the new equilibrium position. It decreases when the wheel leads [third term in Figure (1)].

Also the "damping force" of the pole wheel (illegible) occurs, according to the second term in Equation (1), just like was the case when the pulse produced the eigen oscillation. It is proportional to the oscillation velocity, that is the "slip". It has a negative or braking effect because of the oversynchronous conditions produced by the acceleration.

In addition to these three forces due to the synchronous generator, there is also a fourth force which occurs in the case of a wind propeller drive, which is the result of the propeller wheel characteristic. The torque of the propeller wheel M_{d1} which occurs for synchronous conditions at Point C does not stay constant when synchronous conditions no longer exist. For oversynchronous conditions, it drops off and for undersynchronous conditions, it increases. Assuming that the characteristic is linear, the change in the torque is always proportional to the slip, and shows exactly the same behavior as the damping force of the pole wheel $D_k\frac{dx}{dt}$. The drop in the torque for oversynchronous slip has a braking effect, just like the damping force of the pole wheel.

This means that the decreasing characteristic of the propeller wheel intensifies the damping of the pole wheel. This shortens the time required to assume the new equilibrium state.

In the following we will give a numerical example of this.

First we will investigate the conditions when the new load Point C lies not to the right of the breakaway Point K_1 but either coincides with it or is to the left of it.

When C coincides with K_1 the propeller wheel torque is independent of the rotation rate change for the range of oscillations. This means that there is no increase in the damping by the propeller wheel. The oscillation is a pure eigen oscillation of the generator, according to Equations (15) and (16). On the other hand, when the new load Point C is to the left of the breakaway Point K_1, then the propeller wheel moment increases with increasing rotation rate (that is oversynchronous conditions). This increase results in an attenuation of the damping and therefore, a prolongation of the required transient period, and does not result in an increase as before. By means of a numerical example we will show what happens quantitatively. In particular we will investigate whether the eigen damping of the pole wheel is completely cancelled or if the oscillation can even be built up by this effect, with a subsequent danger of failure.

4. The Equation of the Transient Oscillation Process

In the differential equation for the damped oscillation (1), the second term, which represents the damping term $-D_k \frac{dx}{dt}$ changes by an amount which can be determined using Figure 3. The Points A_1, B and C correspond to the same points in Figure 2. The torque corresponding to Point B is the nominal moment M_{d_n} corresponding to the initial load. Point C is the new equilibrium state with the torque M_{d_1}. It should be noted that if the driving moment of the propeller wheel is assumed to be positive, the opposing load moment of the generator M_{d_n} should be

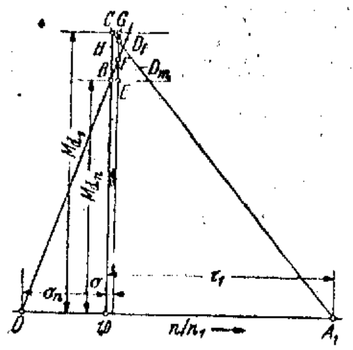

Figure 3. Influence of the propell r wheel characteristic on the damping.

negative and therefore be drawn below the line. In order to determine the equilibrium state we must only compare the two moments; we also show the opposing moments from the generator above the line.

The oblique line passing through the Point B represents the relationship between the damping moments D_m of the pole wheel and its slip $\bar{\sigma}$. For the value of σ assumed in the diagram, which corresponds to oversynchronous conditions, the moment D_m is represented by the segment EF, and is negative because it acts in the same direction as M_{d_n}. By extending the line BF in the backwards direction, we find the intersection Point D and the slip $\bar{\sigma}_n$ at which the damping moment is exactly equal to the nominal moment M_{d_n}. (We should note that for clarity, the value of σ_n has been exaggerated).

For oversynchronous slip conditions σ, the propeller wheel moment is less than the value M_{d_1} by an amount GH. This amount D_F is also proportional to the slip $\bar{\sigma}$ if it is assumed that the propeller wheel characteristic is linear. It can be expressed using the ratio τ_1 of the runaway rotation rate of the propeller wheel (Point A_1) and the synchronous rotation rate, as follows

$$D_F = \frac{\sigma}{\tau_1} M_{d_1}. \tag{20}$$

This moment opposes the drive moment, just like the damping moment D_m.

According to Equation (2) the following value was substituted into the differential Equation (1)

$$D_k = \frac{30}{\pi n R^2} \left(\frac{D_m}{\sigma} \right)$$

Instead of D_m we must use the sum $D_m + D_F$. Considering the propeller wheel characteristic

$$D_k = \frac{30}{\pi n R^2} \left(\frac{D_m}{\sigma} + \frac{D_F}{\sigma} \right)$$

and using Equations (3) and (20), instead of Equation (2a), we find the relationship

$$D_k = \frac{30}{\pi n R^2} \left(\frac{M_{d_n}}{\sigma_n} + \frac{M_{d_1}}{\tau_1} \right)$$

or

$$D_k = \frac{30}{\pi n R^2} \left(\frac{M_{d_n}}{\sigma_n} \right) \left[1 + \frac{M_{d_1}}{M_{d_n}} \frac{\sigma_n}{\tau_1} \right]. \tag{21}$$

If we now set the sudden overload in the torque to be the following

$$\frac{M_{d_1}}{M_{d_n}} = (1 + r),$$ /367

then the amplification factor of the damping in the first square bracket becomes

$$\xi = 1 + (1 + r) \frac{\sigma_n}{\tau_1} . \tag{22}$$

This means that the eigen oscillation period T_{ed} changes and the factor δ required for the exponent y of the decay curve also changes which earlier would have to be multiplied by ξ according to Equation (10). If we retain the earlier value of δ, then instead of Equation (8) we would have to set the following for the eigen oscillation period:

$$T_{ed} = \frac{T_e}{\sqrt{1 - (\xi \delta)^2}} \tag{23}$$

and instead of Equation (13) we would find the following for the exponent y

$$y = 2\pi \xi \delta \left(\frac{T_{rd}}{T_r}\right). \qquad (24)$$

In the oscillation Equation (15), the value of the time constant according to Equation (16) changes as follows

$$T = \frac{T_r}{2\pi \xi \delta}. \qquad (25)$$

The discussions up to the present applies when it is assumed that the new low Point C lies along the right branch of the propeller wheel characteristic. Now if C is already along the curved part of the characteristic, then instead of the variation of the characteristic we must use the inclination at the Point C for relatively small velocity changes. In this case, it is only necessary to draw the tangent to the characteristic at the Point C and then to introduce its segment along the abscissa axis as r_1 in Equations (21) and (22), respectively. r_1 increases the further the point moves upwards. This also decreases the correction termed for the damping.

If C coincides with the breakaway Point K_1, then $r_1 = \infty$ and therefore $\xi = 1$, i.e. in this case the damping due to the pole wheel remains unchanged in this case.

On the other hand, if C is to the less of K_1, then the tangent no longer slopes downwards but slopes upward. Then r_1 becomes negative and therefore the amplification factor becomes $\xi < 1$, i.e., the damping is reduced.

In this connection, the left branch of the characteristic in the present case does not have to be considered to be neutral, for the case of driving by a synchronous generator.

Instead, stable equilibrium results because the differential quotient of the generator characteristic is greater than for the propeller wheel characteristics. The Point K therefore no longer has the meaning of a "breakaway point". (Conclusion to follow.)

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16. Abstract

The damped eigen oscillation of a synchronous generator connected with a fixed network is investigated. It is assumed that the generator is driven by a wind propeller wheel. The influence of the variation of the characteristic of the propeller wheel on the variation of the transient oscillatory behavior is investigated. First the wind velocity increase occur suddenly and then in a continuous fashion. The power control measures including propeller pitch displacement is investigated for preventing overloads on the generator. The danger of resonance is pointed out. This depends on the number of propellers. The question is discussed of whether it is better to use an asynchronous generator instead of a synchronous generator.

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